TITLE: A refrigerator and a method for controlling variable cooling capacity thereof

The present invention relates to a refrigerator comprising a compressor having a fixed or variable cooling capacity and control means for controlling such compressor in response to the temperature inside the refrigerator, as well as to a method for automatically speeding up the cooling time of the food stored in a refrigerator without user interaction and with limited energy consumption. With the term "refrigerator" as used in the description and in the appended claims we mean any kind of domestic refrigerator and freezer. With the term compressor having variable cooling capacity we mean all kind of compressors having the possibility of changing the output, either by changing displacement of the compressor (for instance with the so called free piston compressor) or by changing the speed of the compressor (in case of fixed displacement) either continuously or stepwise. In general, modern freezers and refrigerators have a fast freezing or fast cooling feature. This feature must be activated by the user and consists in keeping the compressor running at its maximum cooling capacity for an appropriate fixed time (i.e. 24 hours). Such a known technique guarantees the maximum cooling speed and is suitable for the fast cooling of large amounts of food. When the amount of food is not very large, it leads to unnecessary food over-cooling and energy waste. On the other hand, the user often forgets to activate the function or he doesn't consider the amount of food large enough to manually activate the function. As a consequence in these cases, the cooling process is relatively slow.

A refrigerator having the features listed in the appended claims solves the above problem.

The present invention provides a control algorithm able to estimate the amount of warm food inserted into the refrigerator or freezer. On the basis of this estimation, the algorithm automatically tunes the compressor response in order to speed-up the cooling process without wasting any energy for unnecessary over-cooling.

In this way the user is not required to activate manually engage the fast cooling function, and any waste of energy, due to over-cooling, is avoided.

The above mentioned and other features and objects of the present invention, and the manner of attaining them, will become more apparent and the invention itself will be better understood by reference to the following description taken in conjunction with the accompanying drawings in which:

- Figure 1 shows a typical temperature trend inside a known freezer when the user puts a quantity of warm food inside the cavity without any "Fast-Freezing" function;
- Figures 2a and 2b show a block scheme describing the logical architecture of the appliance control algorithm (ACA) according to the present invention in case a variable speed compressor or an on/off compressor is respectively used;
- Figure 3 show a typical overshoot probe temperature caused by the introduction of warm food;
- Figure 4 show the main parameters that can be considered to characterized the overshoot shape and to estimate the warm food enthalpy;
- Figure 5 shows a warm food temperature recovery, with an appliance control algorithm according to the present invention;
- Figure 6 shows the auto-fast freezing obtained by estimating the warm food enthalpy just on the basis of the probe overshoot temperature peak; in figure 6a just a door opening was considered, while in figure 6b a door opening with 10 kg of warm food loading was considered;
- Figure 7 shows the auto-fast freezing obtained by estimating the warm food enthalpy on the basis of the probe overshoot temperature peak and on the probe temperature overshoot area; in figure 7a just a door opening was considered, while in figure 7b a door opening with 10 kg of warm food loading was considered.
- Figure 8 highlights the faster recovery and pull-down obtained by considering the temperature probe overshoot area A_{over} in addition to the peak temperature T_{peak};
- Figure 9 a and b show a comparison between a warm food pull-down with the known "Fast-Freezing" function activated and a recovery according to the

present invention respectively, highlighting how the traditional fast freezing function can cause an excessive and unnecessary food "under-cooling" (medium load was considered);

- Figure 10 shows a comparison between energy consumption vs. time obtained with the known fast freezing function (in the working condition shown in fig. 9a) and the energy consumption obtained with a refrigerator according to the present invention (in the working condition of fig. 9b); and
- Figures 11 and 12 show an example of auto fast-freezing function obtained by applying the present invention to an appliance with a variable speed compressor and to an/on off compressor respectively.

With reference to the drawings, in which experimental data were obtained with a Whirlpool side by side refrigerator model *s25brww20-a/g.*, figure 1 shows a typical and well-known temperature trend inside a freezer when the user puts a quantity of warm food inside the cavity. In the first instants the probe temperature rapidly increases. When the user closes the door, the temperature starts going down thanks to the traditional temperature control action, based on a consequent increase of the cooling capacity of the compressor (in the example the speed of the variable speed compressor increases from 1500 rpm to 4000 rpm). The higher is the amount of warm food inside the freezer, the slower the probe temperature tends to go down. An additional important effect of the warm food introduction (figure 1) consists in heating the "cold packages" (we indicate "cold package" the package already stored in the appliance when the warm food is loaded). The present invention relates to a refrigerator and to a method of controlling such refrigerator with the triple objective of controlling the appliance actuators (compressor, valves, damper) in order to:

- maximize the warm food temperature pull-down;
- reduce the "cold package" over temperature; and
- minimize the energy consumption.

Figure 2 shows a block diagram describing the logical architecture of the appliance control algorithm (ACA) according to the present invention. It is

composed of three main blocks: the warm food thermal load estimator (TLE), the probe temperature controller (PTC) and the cooling capacity adapter (CCA).

The first block (TLE) has the purpose of detecting the warm food introduction event and estimating the amount of this warm food.

With the terms "Thermal load" we refers to the warm food enthalpy E defined as

E = (food mass) · (specific food thermal capacity) · (food temperature).

The PTC block has the purpose of controlling the temperature measured by the traditional sensor by providing an appropriated "cooling capacity" request according the above mentioned three objectives.

The cooling capacity adapter CCA converts the cooling capacity request into an appropriated actuator command. Such command can be either the compressor speed if a variable speed compressor is used (figure 2a) or the compressor status (on/off) if a fixed speed compressor is used (figure 2b). In the second case, the block CCA works according to an hysteresis logic, i.e. if the cooling request u(t) is greater than a predetermined value $u(t)_{on}$, the compressor will be switched off, if such cooling request is lower than a predetermined value $u(t)_{off}$, the compressor will be switched off. Of course, it is possible to use another logic for converting the continuous quantity u(t) into a binary value, for instance a PWM (pulse width modulation) technique.

The thermal load estimation TLE block and the probe temperature controller PTC block are within the main features of the present invention.

The TLE block consists on a estimation algorithm based on a accurate analysis of the probe temperature signal in order to obtain the warm food enthalpy E. This is done by processing the shape of the probe temperature overshoot (figure 3) as a consequence to the warm food introduction. With the term of shape factor we mean all the factors that characterize the probe temperature overshoot, and particularly its derivatives, area over an average temperature value (steady state), peak height, overshoot duration, power spectrum or combination thereof. Fig 4 shows the main factors characterizing this temperature overshoot shape and that have to be considered to obtain the warm food temperature enthalpy E, according to the present invention. These main factors are here summarized:

- the probe temperature derivative during the rising phase dTr (average maximum and minimum)
- the probe temperature derivative during the decreasing (slope) phase dTs (average max and min)
- the peak over temperature T_{peak}
- the probe temperature overshoot area A_{over}
- the overshoot duration $\Delta t_{overshhot}$
- the power spectrum of the probe temperature overshoot.

The way in which the above factors are detected/measured is not disclosed here in detail since this is considered within the usual skill of a refrigerator control designer.

Figure 5 shows a warm food temperature recovery, with an appliance control algorithm implementing the present invention. By comparing this chart with the chart in fig 1 (traditional control) it can be noticed how the proposed algorithm performs an appropriate probe "over-cooling". According to the block diagram of figure 2, the probe temperature control block PTC requires the compressor switch off (cooling capacity request = 0) when the warm food temperature (obtained through the TLE block) is considered close enough to the user set temperature.

It is important to notice that the traditional control doesn't perform any probe "under-cooling": as the temperature probe reaches the cut-off temperature, the compressor is shut down but the food is not yet completely cooled. On the contrary, the proposed algorithm performs an appropriate probe "under-cooling" depending on the estimation of the introduced warm food enthalpy provided by the TLE block (figure 2). The TLE block recognizes the warm food introduction, it processes the probe temperature overshoot and provide the PTC block with the estimated warm food enthalpy E. The PTC block decides an appropriated probe temperature undershoot "under-cooling". During this phase, the usual control based on cut-off and cut-on temperature is overruled, i.e. the compressor is no longer switched on and switched off when the temperature inside the refrigerator reaches nominal cut-on and cut-off temperature respectively. During such phase

the cut-off and cut-on temperatures are automatically reduced according to the estimated loaded food enthalpy and are progressively increased to the nominal values in order to provide an energy efficient temperature pull-down. This is clearly shown in figure 5.

After the package loaded into the freezer is considered sufficiently cooled, the usual method of controlling the compressor, in which the compressor is switched off when the cut off temperature is reached, is resumed.

Referring to figure 4, a possible technique for estimating the amount of warm food and to carry out an appropriated probe "over-cooling" is based on the estimation of the A_{over} area, i.e. the integral of the curve representing the increase of temperature above a steady state average temperature T. If A_{over} is the probe temperature area caused by the warm package insertion, the control algorithm drives the compressor to an appropriate speed in order to guarantee an "over-cooling" area A_{under} that is proportional to the area A_{over}, i.e. $A_{under}=k \cdot A_{over}$. The parameter k may depend on the type of appliance. Furthermore, on the same appliance, this parameter may be constant or changed with the working conditions (i.e. external temperature, temperature set by the user etc), and fuzzy logic may be used for purposively adjusting k value.

An alternative technique consists in having an area A_{under} based on time derivative of the probe temperature, i.e. with A_{under} proportional to such derivative either in the temperature rising phase or in the temperature decreasing phase: the lower is the derivative in the decreasing phase, the higher must be A_{under}, the higher is the derivative in the increasing phase, the higher must be A_{under} (time derivative being in absolute value).

Nevertheless other parameters (in addition to the amount of warm food) may affect these parameters (dT_r, dT_s, $\Delta t_{overshoot}$ and A_{over}) and one of these is the external temperature. For this reason, if an external temperature sensor is available in addition to the usual internal temperature sensor, the measure of the above three parameters can be correlated with the measure of external temperature sensor to improve the warm food temperature estimation.

The same techniques described in the previous paragraphs can be used also to decide an appropriated interval time Dt in which the compressor must be forced to run at an appropriated level of power (for instance at the maximum one).
Of course any combination of the previous techniques can be used.
Fuzzy logic and "neural network" techniques can be used for this kind of application. For examples a control algorithm based on a set of Fuzzy rules can receive as input all the mentioned parameters shown in figure 4 and convert them into an estimation of both the mass and the temperature of the inserted food or its enthalpy E (as the product of thermal mass by temperature). This estimation can then be passed to a second task which converts it into a request of compressor cooling capacity u(t) and it can provide one or more additional parameters such as: probe sub-cooling area A_{under}, cut-off temperature T_{off}, interval time Dt in which the compressor must be forced to run at an appropriate level of power (if different levels of power are available).
Alternatively or in addition to such kind of technical solution, a temperature control algorithm based on the PID (Proportional-derivative-integral) technique can obtain the control.
With such a kind of algorithm, the compressor cooling capacity request u(t) will depend on the error temperature e(t) according to the following formula:

$$u(t) = Kp * [e(t) + \frac{1}{Ti} * \int_0^t e(\tau) d\tau + Td * \frac{de(t)}{dt}]$$

Where the temperature error *e(t)* is defined as: *e(t)= Tprobe-Ttarget,* Ti is the integral time, Td is the derivative time, Ttarget is a temperature reference depending on the user set temperature and Kp is a predetermined coefficient.
The integral component plays the main role in adapting the cooling capacity to the amount of warm food. In fact it is proportional to the area of the error *e(t)* along the time axes. During a recovery, this area is significantly affected by the amount of warm food: the higher is the amount of warm food, the longer *e(t)* tends to be "high" (>0) with a consequent increasing of its area (see area A_{over} in fig 4). This condition leads to a progressive increasing of the compressor cooling

capacity u(t). Furthermore, the integrative component guarantees an appropriate probe "under-cooling" to compensate the positive area caused by the insertion of the warm food. To enhance this effect, an adaptive PID can be used. A "steady state PID" will control the appliance temperature when no disturbances affect the system (no door opening, no food introduction). Once door opening and food introduction events are detected, the "steady state PID" will be disabled and a "pull-down PID" algorithm will be engaged. Such "pull-down PID" will provide a fast and energy efficient warm food temperature pull-down. This can be obtained by adjusting the Ti parameter according to the following criteria:

- during the steady state, Ti will be set to its nominal value ($Ti= Ti_N$);
- once a warm food introduction is detected and the probe temperature overshoot starts, the Ti is reduced by a k1 factor ($Ti=Ti_N/k1$, $k1>=1$). This will enhance the dependence of the integral part of the PID from the probe temperature over shoot area A_{over} that is one of the main factors affected by the warm food enthalpy;
- at the end of the probe temperature overshoot (when e(t) pass from negative to positive) the Ti will be increased by a k2 factor: ($Ti=Ti_N*k2$, $k2>=1$). This will slow down the integral part discharge with a consequent probe temperature over-cooling area. Such over-cooling will be proportional to the previous temperature overshoot area and, by consequence to the warm food enthalpy. The adjustment of Ti (and/or of other parameters as Td and Kp) can act together with or replacing the well-known "anti wind-up" technique in which the integrative part of the temperature error may or not be saturated to a pre determinate value.

It is important to highlight the fact that the effectiveness of the invention in providing an appropriate warm food temperature pull-down depends on the precision of the food enthalpy estimation. The more accurate is the estimation, the more precise will be the pull-down in respect to the above-mentioned triple objective. The quality of the estimation mainly depends on what probe temperature overshoot parameters (see fig 4) are considered by the TLE block to obtain the warm food enthalpy estimation. In particular an intuitive solution would

suggest to estimates the food enthalpy just on the basis of the peak temperature T_{peak} without any consideration about the shape of the overshoot probe temperature. Such kind of solution wouldn't get the appliance control algorithm able to correctly recognize the amount of the warm food and would provide a wrong temperature pull-down in the sense that it can provide an excessive food under-cooling when the amount of warm food is low (with a consequent waste of energy). Or it can provide a not enough fast pull-down in presence of large amount of warm food. This fact is highlighted in figures 6a and 6b. These figures show the pull down obtained with an appliance control that estimates the food enthalpy just on the basis of the probe overshoot peak temperature (Tpeak) and set a continuous compressor run time proportional to Tpeak. Figure 6a show the response of such kind of algorithm to a door opening of 3 minutes without any food introduction. Figure 6b shows the behavior of the same algorithm in response to a door opening with 10 Kg of warm food introduction at the external ambient temperature (20°C). In both the cases, the peak temperature value (Tpeak) is roughly the same and the algorithm decides for 2 hours of compressor continuous running. After 2 hours, the compressor will be switched off according to the normal cut-off temperature. It can be noticed how the algorithm performs a good cold package temperature recovery in the first condition (figure 6a): the compressor is switched off as the cold package temperature returns to the steady state value: any additional sub-cooling would cause a waste of energy. When 10 kg of warm package are introduced (figure 6b) the algorithm decides again for 2 hours of compressor continuous running (being the T_{peak} value the same). After two hours, the temperature is still above the cut-off value; the control algorithm can decide to keep the compressor in a switched on condition up to the cut-off temperature is reached. But in this case the performances of the control are not optimal. In fact the compressor is switched off when the cold package is still more than 3°C above the steady state value and the warm package is still 5°C up the steady state value.

Figures 7a and 7b show the behavior of a control appliance in which the estimation of the warm food enthalpy is based on both the peak temperature and

the overshoot area. The disturbances here considered are exactly the same considered with the previous algorithm (3 minutes of door opening without load introduction, door opening with 10 kg of load introduction). In particular an adaptive PID according to the above mentioned idea was here considered as a control algorithm (with k1=1 and k2=2, Ti =3600 sec.).

By analyzing figures 7a and b, it can be noticed how the pull-down and recovery are correctly performed in both the conditions proving the capability of the algorithm in adapting automatically the compressor response and the probe temperature over-cooling to the amount of introduced warm load. In fact in the first case the compressor was switched off when the cold package was close enough to the steady state value (just 0.5°C above the steady state value). In the second case (10 kg of warm load introduction), again the compressor was switched off when the warm packages reached the steady state value and the cold package is just 1°C over steady state the temperature and it returns to its steady state value in half of the time. Furthermore, it can be noticed how in both the cases the algorithm doesn't restore immediately the cut off and the cut-on temperatures after the first switch off but it increases them progressively up to the steady state value. This is done in order to have a fast package recovery and pull-down avoiding excessive cold probe temperatures which would cause waste of energy (the colder is the probe temperature, the colder is the evaporator temperature and, by consequence, the less efficient is the thermodynamic cycle).

Figure 8 highlights the recovery performed by the two considered algorithms.

The main advantages of the present invention are as follows. The algorithm adapts the compressor response to the warm thermal mass avoiding any waste of energy for unnecessary over-cooling. In particular, figure 9a shows the effects of the traditional fast freezing function manually activated by the user: in this case "medium load" quantity of warm food has been inserted into the freezer. The traditional fast freezing function keeps the compressor running at its maximum capacity for 24 hours with a consequent under cooling of the food with a consequent waste of energy. Figure 9b shows the automatic fast freezing performed by the method according to the present invention in the same working

condition of figure 9a: without any user interaction the same amount of warm food is rapidly recovered without unnecessary food "under-cooling". Figure 10 shows the comparison between the energy consumption in the two above cases. The method according to the invention is completely automatic, this means that the user is not required to activate any function. So the risk of a slow temperature recovery, when the user forgets to activate the fast freezing function present in known refrigerators, is avoided. Finally it is important to underline that the present invention can be applied both for appliance with variable capacity compressor and on-off compressor. According to the block scheme of fig. 2, In case of variable speed compressor, the cooling request provided by the PTC block will be converted into a speed request through an appropriated curve (ex. linear). In case of a traditional on/off compressor, the cooling request will be converted into a compressor state command according with an appropriated logic (hysteresis, PWM). Figures 11 and 12 show an example of application according to the invention to a variable speed compressor and to an on/off compressor respectively.

Even if the description is mainly focused on an example of algorithm applied to a freezer, the same algorithm can be used also in a refrigerator or in a fresh food compartment of an appliance having more than one refrigerating cavity.